Application

for

United States Letters Patent

To all whom it may concern:

Be it known that,

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have invented certain new and useful improvements in

SEMICONDUCTOR OPTICAL AMPLIFIER USING LASER CAVITY
ENERGY TO AMPLIFY SIGNAL AND METHOD OF FABRICATION THEREOF

of which the following is a full, clear and exact description:

SEMICONDUCTOR OPTICAL AMPLIFIER USING LASER CAVITY ENERGY TO AMPLIFY SIGNAL AND METHOD OF FABRICATION THEREOF

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Ser. No. 09/972,146, filed October 4, 2001, which is incorporated by reference herein.

FIELD

This patent specification relates to optical amplifiers. More specifically, it relates to a semiconductor optical amplifier that amplifies an optical signal using energy from one or more nearby and/or intersecting laser cavities.

BACKGROUND

As the world's need for communication capacity continues to increase, the use of optical signals to transfer large amounts of information has become increasingly favored over other schemes such as those using twisted copper wires, coaxial cables, or microwave links. Optical communication systems use optical signals to carry information at high speeds over an optical path such as an optical fiber. Optical fiber communication systems are generally immune to electromagnetic interference effects, unlike the other schemes listed above. Furthermore, the silica glass fibers used in fiber optic communication systems are lightweight, comparatively low cost, and are capable of very high-bandwidth operation.

Optical amplifiers are important components of optical communications links. Optical amplifiers are commonly used as (i) power amplifiers at the source end of an optical communications link, (ii) line amplifiers along the optical signal transmission path, and (iii) preamplifiers at the receiving end of the optical communications link, and have other uses as well.

In general, the two primary types of optical amplifiers are optical fiber based amplifiers, such as erbium doped fiber amplifiers (EDFAs) and Raman amplifiers, and semiconductor optical amplifiers (SOAs). EDFAs are widely used in line amplifiers and other applications requiring high output power, high data rates, and low noise. However,

5   EDFAs are quite bulky, having a typical fiber length of about 30 feet, and require the presence of a separate pumping laser to operate. Accordingly, EDFAs are difficult to incorporate into confined spaces, and are certainly not amenable to circuit-board-level or chip-level integration.

SOAs, on the other hand, are small in size and conveniently integrated into small

10   devices. An SOA generally resembles a semiconductor laser structure, except that the end mirrors are replaced by antireflection coatings. In such devices the product of the gain and the reflectivity is less than one so that the device does not oscillate. Rather, the device is used to amplify an incoming optical signal as it passes through the device. Such devices are often called traveling wave amplifiers, which highlights the fact that the

15   optical signal does not pass back and forth within the device, but merely passes through it essentially only once. SOAs generally yield lower output power and higher noise levels as compared to EDFAs, and/or are restricted to lower data rates at high output power due to pattern dependent amplitude variations. Research continues toward improving the performance of SOAs, including making SOAs with higher power and lower noise

20   characteristics, and/or that are capable of operating at higher data rates at high input power without suffering significant pattern dependent amplitude fluctuations.

Crosstalk is one of the primary troublesome noise sources in conventional SOAs. Crosstalk, or cross-channel modulation, involves data-dependent gain fluctuations at high output levels from the SOA, and can occur for either time-multiplexed or wavelength-

25   multiplexed data. Crosstalk arises from gain saturation effects in an SOA. These effects can be understood by recalling that SOA devices rely on the phenomenon of stimulated emission to provide the necessary amplification. Stimulated emission, in turn, requires the establishment of a population inversion. In typical SOAs or lasers a population inversion is evidenced by the presence of a specified carrier density. When a sufficiently

30   large optical signal is passed through the amplifier, the population inversion is substantially reduced or depleted, *i.e.* the gain of the SOA is saturated, and is

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reestablished only over some finite period of time. Consequently, the gain of the SOA will be reduced for some period of time following the passage of the signal through the amplifier, a time period commonly denoted as the amplifier gain recovery time.

When the gain medium becomes saturated due to a high signal level on a first

5 channel, changes are induced in the signal level of a second channel because the saturated gain medium cannot properly amplify both channels. Since gain is modulated by the first signal, this modulated gain is impressed on the second signal. Thus, for wavelength division multiplexed (WDM) systems in which a plurality of channels at $\lambda_1, \lambda_2, ..., \lambda_N$ are present in a common optical signal, gain saturation induced by a first channel at λ_1 can

10 produce unwanted level changes (*i.e.*, errors) in a second data channel at λ_2, and vice versa.

Crosstalk can be reduced by keeping the SOA out of gain saturation for the data rates, signal levels, and number of channels on the optical signal of interest. If the SOA is operated near gain saturation levels, crosstalk may be reduced by making the "off"

15 portion of the signal duty cycle longer in comparison to the gain recovery time, *i.e.*, by slowing down the data rate. In general, an SOA will have reduced crosstalk effects if (i) its saturation power P_{SAT}, *i.e.*, the input optical power level for which the SOA gain is reduced to a predetermined percentage of its nominal value, is increased, and/or (ii) its gain recovery time is decreased. As used herein, an SOA has increased gain stability if

20 (i) its saturation power P_{SAT} is increased without a concomitant increase in gain recovery time, (ii) its gain recovery time is decreased without a concomitant decrease in saturation power P_{SAT}, or (iii) both (i) and (ii) occur.

Several methods for dealing with crosstalk problems are discussed in U.S. Pat. 5,436,759, which is incorporated by reference herein. One particularly appealing strategy

25 is to place a transverse laser across the SOA such that the laser's gain medium and the SOA's signal gain medium share an overlapping region. The lasing cavity is operated above threshold and the gain of the laser is clamped to overcome the losses of the cavity. As used herein, a laser cavity is gain-clamped and lasing when it is excited by a bias current greater than a threshold current. When the transverse laser is gain-clamped, gain

30 along the SOA signal path is stabilized. The transverse lasing enhances the establishment and maintenance of a population inversion in the overlapping region, resulting in both

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increased saturation power and a decreased gain recovery time due to increased photon density in the laser cavity. Advantageously, independent lasing only builds up in the transverse direction and does not corrupt the quality of the amplified signal. Other methods in which the gain media of SOAs is coextensive with the gain media of

5 transverse lasers are discussed in Francis, et. al., "A Single Chip Linear Optical Amplifier," IEEE Optical Fiber Communication Conference, Anaheim, CA (2001), which is incorporated by reference herein, and in U.S. Ser. No. 09/972,146, *supra*.

Amplified spontaneous emission (ASE) is another primary troublesome noise source in conventional SOAs. ASE arises from random, spontaneous energy state drops

10 in a small fraction of the excited carriers of the gain medium. Light emitted as a result of these energy state drops is generally random in direction and wavelength. Some of this light will be emitted in the direction of signal propagation and will therefore be amplified as it propagates, resulting in output background noise signal similar to white noise. For good performance, it is generally desirable to keep the amplified signal levels at least 10

15 dB higher than ASE levels.

One potential disadvantage of an SOA having a gain medium coextensive with the gain medium of a transverse laser cavity is that ASE levels in the output can be relatively high. This is because the population inversion of the gain medium, and therefore the number of carriers experiencing spontaneous energy state drops, is

20 maintained at high levels by the transverse lasing field. Other potential drawbacks, include polarization sensitivity, output power limitations, and reduced coupling efficiency are related to the generally thin nature of the gain medium layer itself in such devices. Whereas the width of the signal path is usually on the order of 8 μm for single-mode propagation, the height of the signal path is generally limited to the thickness of the

25 gain medium layer, which is often less than 1 μm. Thus, the signal waveguide has a small cross-section (as compared to single-mode waveguides having larger aspect ratios), which limits overall power carrying capacity and reduces coupling efficiency with external planar lightwave circuits and optical fibers. Moreover, the small height dimension causes the signal waveguide to prefer one light polarization over another,

30 causing the SOA to be polarization sensitive and difficult to couple to optical fibers.

The proposed designs discussed in U.S. Pat. 5,436,759, *supra*, also suffer from other shortcomings that can reduce the effectiveness or usefulness of the SOA device and/or cause difficulty in reliably fabricating the device. For example, while the electrical pumping current applied to the laser cavity dictates the *presence* of gain-

5   clamped operation (below-threshold current yields unclamped operation, above-threshold yields clamped operation), there are no controls provided that allow for dynamic control of the actual *amount* of gain once the gain is clamped. As another example, the layers of the single active medium ('759 patent, Fig. 1) can be difficult to construct reliably with consistent thickness across the entire lateral area to be covered. In addition, the

10   semiconductor layers may contain local defects such as crystal dislocations, pitting, voids, etc. Such defects in the epitaxial growth can be a point of lower electrical resistance than the surrounding epitaxial areas. The higher electrical current flowing through these points of lower electrical resistance can create "hot spots" which cause non-uniform gain in the effected areas. In addition to the less than optimal performance

15   resulting form the non-uniform gain, the "hot spots" can be a source of excessive current drain and premature device failure. As another example, undesired parasitic modes or uneven lasing may arise due to lack of electrical isolation among laser cavity segments at intersections with the signal gain medium.

The approach discussed in Francis, *supra*, in which the signal waveguide and a

20   vertical cavity surface emitting laser (VCSEL) share the same active region, can also suffer from non-uniform current flows and hot spots due to defects in crystal growth and non-uniform epitaxial layers. Moreover, such devices can have limited output power due to the small gain medium volume of VCSELs, as well as for other reasons.

U.S. Pat. 5,291,328, which is incorporated by reference herein, discusses a

25   semiconductor optical amplifier having an active layer vertically separated from a signal waveguiding layer in order to reduce polarization sensitivity. The active layer and passive waveguide layer are vertically collinear between the input and output facets of the device. According to the discussion of the '328 patent, by using a structure which is analogous to a buried-heterostructure distributed feedback laser having a waveguiding

30   layer and an active layer in close association, but without the grating, it is possible to achieve high gain and low polarization sensitivity over a usefully broad wavelength

range. However, the device discussed in the '328 patent is not designed for lasing action to occur in the active layer, having antireflective coatings at the end facets, and would accordingly suffer from the crosstalk problems discussed *supra*. Moreover, the device can also suffer from non-uniform current flows and hot spots due to defects in crystal

5 growth and non-uniform epitaxial layers, although such problems are less relevant because the device does not achieve lasing action anyway.

U.S. Pat. 4,742,307, which is incorporated by reference herein, also discusses a semiconductor optical amplifier having an active layer vertically separated from a passive waveguide layer, for the discussed purpose of reducing ASE noise in the output. The

10 active layer and passive waveguide layers are vertically collinear between the input and output facets of the device. Notably, the device of the '307 discussion has increased separation between the active layer and the passive waveguide layer near the ends of the device for easier coupling between external fibers and the signal path ('307 patent, Figs 1A, 1B, 7). However, this separation is in the vertical direction, and must therefore be

15 achieved by differential growth processes or other more complicated fabrication steps. This is particularly troublesome where appreciable separations approaching 8 μm or more are needed for efficient coupling into fibers. Moreover, as with the device of the '328 patent, the device of the '307 patent is not designed for lasing action to occur in the active layer, and would accordingly suffer from the crosstalk problems discussed *supra*. The

20 device can also suffer from non-uniform current flows and hot spots due to defects in crystal growth and non-uniform epitaxial layers although, as with the '328 device, these problems are less relevant because the device does not achieve lasing action anyway.

Accordingly, it would be desirable to provide a semiconductor optical amplifier (SOA) having reduced crosstalk effects while also having reduced polarization

25 sensitivity.

It would be further desirable to provide an SOA having reduced crosstalk effects while also having reduced amplified spontaneous emission (ASE) noise levels.

It would be even further desirable to provide an SOA having reduced crosstalk effects while also allowing dynamic adjustment of gain during gain-clamped operation.

30 It would be still further desirable to provide such an SOA capable of achieving a variable gain characteristic along its length.

It would be even further desirable to provide such an SOA in which signal power capacity is increased and coupling efficiency with optical fibers and planar lightwave circuits is increased.

It would be even further desirable to provide such an SOA that can be reliably
5   fabricated.

It would be still further desirable to provide such an SOA that is more operationally robust against the presence of local defects that may occur during device fabrication.

10   **SUMMARY**

According to a preferred embodiment, a semiconductor optical amplifier (SOA) apparatus and related methods are provided for amplifying an optical signal, the SOA comprising a signal waveguide for guiding the optical signal along a signal path, the SOA further comprising one or more laser cavities having a gain medium lying outside the
15   signal waveguide. Although lying outside the signal waveguide, the gain medium of the laser cavity is sufficiently close to the signal waveguide such that, when the gain medium is pumped with an excitation current, the optical signal traveling down the signal waveguide is amplified by an evanescent coupling effect with the laser cavity. When the gain medium is sufficiently pumped to cause lasing action in the laser cavity, gain-
20   clamped amplification of the optical signal is achieved. An SOA according to the preferred embodiments provides for sufficient signal amplification while also providing a more symmetric waveguide for the optical signal to follow, thereby reducing polarization sensitivity, increasing signal power capacity levels, and increasing coupling efficiency with planar lightwave circuits and optical fibers. Because the ASE generated by the gain
25   medium layer does not couple well into the signal waveguide, output ASE levels are reduced.

In one preferred embodiment, one or more laser cavities is provided, each laser cavity comprising a main segment that evanescently couples with the optical signal, each laser cavity further comprising an auxiliary segment that is electrically isolated from the
30   main segment, the main segment and the auxiliary segment being provided with separate electrical excitation currents. The laser cavities are also electrically isolated from one

another. The electrical excitation currents provided to the various laser cavities and cavity segments are varied so as to achieve improved performance with respect to one or more operating characteristics, and/or to achieve desired signal processing objectives. In another preferred embodiment comprising a plurality of laser cavities adjacently

5 positioned between the optical signal input and the optical signal output, amplified spontaneous emission (ASE) noise performance is improved by tailoring the amount of current supplied to the auxiliary segments of successive laser cavities. In other preferred embodiments, an array of two or more signal waveguides share a common set of transverse laser cavities.

10 In one preferred embodiment, extraneous output energy lying within the wavelengths of operation of the SOA is avoided by including distributed Bragg reflector (DBR) gratings and/or distributed feedback (DFB) gratings in one or more of the laser cavities. In another preferred embodiment, the period of the DBR and/or DFB gratings is varied among successive laser cavities so that their respective lasing wavelengths differ,

15 thereby avoiding undesired coupling effects and/or injection locking effects. In another preferred embodiment, coupled-cavity lasers are used for enhancing single-frequency operation with greater side mode suppression. In another preferred embodiment, gain curve peaks of the active medium within a given laser cavity are separately manipulated with differing currents/junction temperatures to increase device efficiency. In other

20 preferred embodiments, novel integrations are provided that include an SOA having signal amplification energy provided by a nearby laser cavity, in which the SOA is integrated onto a common substrate with a tunable vertical cavity coupler, a photodetector, and a return-to-zero signal modulator, respectively.

In other preferred embodiments, one or more of the above features relating to

25 using DFB/DBR gratings, varying cavity segment currents, improving ASE noise performance, using coupled-cavity lasers, avoiding injection locking effects, manipulating gain curve peaks, integration with a tunable vertical cavity coupler, integration with a photodetector, integration with an RZ signal modulator, arraying of the signal waveguides, and other features described herein are used in conjunction with an

30 SOA having a laser cavity gain medium that is coextensive with the gain medium of the signal waveguide.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a perspective view of a semiconductor optical amplifier (SOA) in accordance with a preferred embodiment;

FIG. 2 illustrates a perspective view of an SOA in accordance with a preferred embodiment;

FIG. 3 illustrates a top view of the SOA of FIG. 2;

FIG. 4 illustrates a first cross-sectional view of the SOA of FIG. 2;

FIG. 5 illustrates a second cross-sectional view of the SOA of FIG. 2;

FIG. 6 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 7 illustrates a conceptual plot of emitted laser power versus excitation currents in the SOA of FIG. 6;

FIG. 8A illustrates a conceptual plot of SOA gain versus output signal power in the SOA of FIG. 6;

FIG. 8B illustrates a conceptual plot of emitted laser power versus excitation currents in the SOA of FIG. 6;

FIG. 8C illustrates a conceptual plot of SOA gain versus output signal power in the SOA of FIG. 6;

FIG. 9 illustrates a plot of laser gain medium gain versus wavelength and associated operational wavelengths of the SOA of FIG. 6;

FIG. 10 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 11 illustrates a cross-sectional view of the SOA of FIG. 10;

FIG. 12 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 13 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 14 illustrates a cross-sectional view of the SOA of FIG. 13;

FIG. 15 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 16 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 17 illustrates a top view of an SOA in accordance with a preferred embodiment;

5 FIG. 18 illustrates steps for fabricating an SOA in accordance with a preferred embodiment;

FIGS. 19A and 19B illustrate perspective views of an SOA in accordance with a preferred embodiment;

FIG. 20 illustrates a top view of an SOA in accordance with a preferred

10 embodiment;

FIG. 21 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 22 illustrates a top view of an SOA in accordance with a preferred embodiment;

15 FIG. 23 illustrates a conceptual plot of emitted laser power versus excitation currents in the SOA of FIG. 22;

FIG. 24A illustrates a conceptual plot of signal gain versus signal power in the SOA of FIG. 22;

FIG. 24B illustrates a conceptual plot of emitted laser power versus excitation

20 currents in the SOA of FIG. 22;

FIG. 24C illustrates a conceptual plot of signal gain versus signal power in the SOA of FIG. 22;

FIG. 25 illustrates a perspective view of an SOA with an integrated tunable vertical coupler filter in accordance with a preferred embodiment;

25 FIG. 26 illustrates a perspective view of an SOA with an integrated tunable vertical coupler filter and integrated photodiode detector in accordance with a preferred embodiment;

FIG. 27 illustrates a perspective view of an integrated return-to-zero (RZ) signal generator in accordance with a preferred embodiment;

30 FIG. 28 illustrates a perspective view of an integrated return-to-zero (RZ) signal generator with chirp tailoring capability in accordance with a preferred embodiment.

FIG. 29 illustrates a top view of an SOA in accordance with a preferred embodiment;

FIG. 30 illustrates a top view of an SOA in accordance with a preferred embodiment;

5   FIG. 31 illustrates a top view of an SOA in accordance with a preferred embodiment and related explanatory gain medium characteristic curves;

FIG. 32 illustrates a top view of an SOA array in accordance with a preferred embodiment;

FIG. 33 illustrates a top view of an SOA array in accordance with a preferred

10 embodiment; and

FIG. 34 illustrates a top view of an SOA array in accordance with a preferred embodiment.

DESCRIPTION

15   FIG. 1 illustrates a simplified perspective view of a semiconductor optical amplifier (SOA) 102 in accordance with a preferred embodiment. SOA 102 receives an optical signal 104 at an input, guides the optical signal 104 along an optical path 105 while also amplifying it, and provides an amplified version of the optical signal 104 at an output as indicated in FIG. 1. SOA 102 comprises a signal guiding layer 108, a ridge

20 element 110, and a first cladding layer 112 positioned as shown in FIG. 1, the guiding layer 108 having a refractive index that is higher than the refractive indices of the ridge element 110 and the first cladding layer 112 such that the optical signal 104 is vertically confined. By way of example, the guiding layer 108 comprises passive waveguiding p-doped indium gallium arsenide phosphide, $e.g.$, $In_{0.95}Ga_{0.05}As_{0.1}P_{0.9}$, while the ridge

25 element 110 and first cladding layer 112 comprise p-doped indium phosphide (p-InP). It is to be appreciated, however, that other material systems having the appropriate characteristics may be used. Ridge element 110 also provides for horizontal confinement of the optical signal 104, such that the optical path 105 generally follows underneath the ridge element 110 between the input and the output of the SOA 102. Collectively, the

30 guiding layer 108, the ridge element 110, and the first cladding layer 112 form a signal waveguide 101 defining the optical path 105 as indicated in FIG. 1. In other preferred

embodiments, the signal waveguide 101 is similar to any of a variety of ridge waveguide structures such as those described in Agrawal and Dutta, *Semiconductor Lasers*, 2nd ed., Kluwer Academic Publishers (1993) at Chapter 5, which is incorporated by reference herein.

5   SOA 102 further comprises a gain medium layer 114, a laser waveguiding layer 116, and a second cladding layer 118 positioned as shown in FIG. 1. Gain medium layer 114 may interchangeably be called an active layer herein. The laser waveguiding layer 116 and second cladding layer 118 are shaped to form a rib element 120 longitudinally extending from one end of the device to the other. Gain medium layer 114 has a

10   refractive index greater than the refractive index of the first cladding layer 112 and similar to the refractive index of the laser waveguiding layer 116, which in turn has a refractive index greater than the refractive index of the second cladding layer 118. By way of example, the gain medium layer 114 comprises bulk active indium gallium arsenide phosphide, *e.g.*, $In_{0.7}Ga_{0.3}As_{0.7}P_{0.3}$, or may comprise multiple quantum wells

15   (MQWs) according to a InGaAsP/InGaAs/InP material system. The laser waveguiding layer 116 comprises passive waveguiding n-doped indium gallium arsenide phosphide, *e.g.*, $In_{0.95}Ga_{0.05}As_{0.1}P_{0.9}$, and the second cladding layer 118 comprises n-doped indium phosphide (n-InP), these layers being formed on top of an indium phosphide (InP) substrate 122. Again, however, other material systems having the appropriate

20   characteristics may be used.

      It is to be appreciated that while the SOA 102 comprises a p-over-n buried heterostructure laser in which a signal waveguide is placed above the gain medium layer on the "p" side, a complementary structure in which the signal waveguide is placed on the "n" side of the gain medium is of course within the scope of the preferred

25   embodiments. Indeed, the complementary implementation could be advantageous in that n-doped signal waveguides typically have lower optical absorption losses than p-doped signal waveguides. For simplicity and clarity of disclosure, however, the preferred embodiments are described herein as having a signal waveguide on the "p" side of the gain medium layer.

30   A lower electrical contact (not shown) is provided on a bottom side of substrate 122, comprising for example sputtered Ti/Pt/Au. An upper electrical contact (not shown)

is provided along the surface of the SOA 102, comprising for example Ti/Au, such that an electrical current flowing between the upper and lower electrical contacts passes through the gain medium layer 114 near the rib element 120. Accordingly, an index-guided edge emitting laser cavity 124 is formed (i) longitudinally between the front and

5 rear end mirrors, (ii) vertically between the first and second cladding layers 112 and 118, with (iii) lateral confinement being provided by the presence of the rib element 120. When the electrical current through the gain medium 114 inside the laser cavity 124 exceeds a threshold current, lasing action occurs. In other preferred embodiments, the laser cavity 124 is similar to any of a variety of rib waveguide structures such as those

10 described in Agrawal, *supra* at Chapter 5.

If necessary for proper lasing operation, partially reflective end mirrors (not shown) are provided at each longitudinal end of the SOA 102 at the rib element 120. If the facets at each longitudinal end of the SOA 102 are cleaved (as opposed to being dry-etched), there may be sufficient reflectivity to obviate the need for the end mirrors.

15 Generally speaking, it is desirable to have end facet reflectivities around the rib element 120 that are not less than 10 percent, and preferably 30 percent or greater, so that lasing action is facilitated in the laser cavity 124. Antireflective coatings (not shown) are provided at each longitudinal end of the SOA 102 at the entry and exit points of the signal waveguide 101.

20 As indicated in FIG. 1, for a first longitudinal interval of length d_0 the signal waveguide 101 does not lie directly above the laser cavity 124 and the optical signal is not amplified. This is also the case for a final longitudinal interval of length d_1. It is preferable to keep the distances d_0 and d_1 short in order to minimize loss in those intervals and to keep overall device dimensions small. However, to facilitate coupling to external

25 optical devices, there must be sufficient lateral separation between the facets of the laser cavity 124 and the input and output of the signal waveguide 101, *e.g.*, about 10 μm or more. This, in turn, requires sufficiently large distances d_0 and d_1 such that large angles in the optical signal path are not encountered. By way of example and not by way of limitation, signal losses are tolerable if the signal path angles are kept below about 1

30 degree, which in turn requires distances d_0 and d_1 to be on the order of about 1 mm. In other preferred embodiments, less desirable but still tolerable signal losses are incurred if

the signal path angles are kept below about 10 degrees, which in turn requires distances d_0 and d_1 to be on the order of about 100 μm. In still other preferred embodiments, the distances d_0 and d_1 can be drastically reduced by using certain photonic crystal planar circuits that have been shown to guide light at 1550 nm around sharp corners having radii

5 of curvature similar to the wavelength of the light, as described in Loncar et. al., "Waveguiding in Planar Photonic Crystals," Applied Physics Letters Vol. 77, No. 13 (September 25, 2000) at pp. 1937-1939, and in Joannopoulos, "Molding the Flow of Light," M.I.T. 2001 Physics Annual (2001) at pp. 32-43, each of which is incorporated by reference herein.

10 For a second longitudinal interval of length L_{AMP}, the signal waveguide 101 vertically coincides with the laser cavity 124 to form an evanescent coupling region. When the laser cavity 124 is lasing, or when the laser cavity 124 is not lasing but a sufficient population inversion exists due to an electrical excitation current, the optical signal 104 is amplified by an evanescent coupling effect with the laser cavity 124 in the

15 evanescent coupling region. The particular lateral dimensions and layer thicknesses required to facilitate such evanescent coupling between the signal waveguide 101 and the laser cavity 124 depends on factors such as the particular material compositions, refractive indices, doping levels, signal powers, wavelength ranges used, and other factors. In light of the present disclosure, however, one skilled in the art would be readily

20 able to determine a suitable set of parameters and implement an SOA in accordance with the preferred embodiments.

By way of example and not by way of limitation, for propagation and amplification of a single-mode WDM signal near the 1550 nm range for a device based on an InP/InGaAsP material system, in one preferred embodiment the width of the ridge

25 element 110 is approximately 8-10 μm, the thickness of the guiding layer 108 is about 3 μm, the thickness of the first cladding layer 112 is in the range of about 0.5-2.0 μm, and the thickness of the gain medium layer 114 is about 0.2 μm. The thickness of the laser waveguiding layer 116 is about 0.2 μm in the non-rib areas and about 0.4 μm in the area of the rib element 120, which has a lateral width of approximately 8-10 μm. The

30 amplification distance L_{AMP} may be in the range of 0.2 mm-2 mm, although this may be varied significantly depending on the required overall amplification and the signal gain

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per unit length.

In another preferred embodiment, the thickness of the guiding layer 108 is 0.4 µm, the thickness of the first cladding layer 112 is about 1 µm, and the thickness of the gain medium layer 114 is about 0.2 µm. In yet another preferred embodiment, the

5   thickness of the guiding layer 108 is about 0.23 µm, the thickness of the first cladding layer 112 is about 0.16 µm, and the thickness of the gain medium layer is about 0.18 µm. It is to be appreciated, however, that while the above dimensions are examples of suitable ones, one skilled in the art could readily determine a variety of different operable ranges and parameter combinations for an SOA in accordance with the preferred embodiments

10 in light of the present disclosure.

Some operating ranges for the SOA 102 are presented here by way of example and not by way of limitation. A typical input signal power is in range of 10-100 µW, a typical lasing power for the laser cavity 124 is in the range of 5-50 mW, a typical signal gain is in the range of 20-30 dB, and a typical output signal power is in the range of 1-

15 100 mW. It is to be appreciated, however, that one skilled in the art could readily adapt the SOA 102 for use in substantially higher or lower optical power environments in light of the present disclosure, with resulting devices being capable of widely differing input signal power levels, lasing power levels, signal gain levels, and/or output power levels, without departing from the scope of the preferred embodiments.

20   The SOA 102 in accordance with the preferred embodiments provides for sufficient signal amplification while also providing a more symmetric waveguide for the optical signal to follow, thereby reducing polarization sensitivity, increasing signal power capacity levels, and increasing signal coupling efficiencies as compared to devices requiring the optical signal to propagate along the gain medium layer itself. Also,

25 because the ASE generated by the gain medium layer does not couple well into the signal waveguide, output ASE levels are reduced.

The laser cavity 124, as well as the laser cavities *infra* that provide the amplification energy for an optical signal propagating down a nearby (or intersecting) signal waveguide, can generally be referred to as excitation lasers or ballast lasers due to

30 their role in the SOA device. The light emitted from the laser itself is not used. Rather, the laser is used as an energy source for amplifying an optical signal different than the

laser's own beam.

FIG. 2 illustrates a perspective view of an SOA 200 in accordance with a preferred embodiment. SOA 200 comprises material layers 208, 212-218, and 222 similar to the material layers 108, 112-118, and 122 of FIG. 1, respectively. However,

5   SOA 200 comprises a straight ridge element 210 laterally defining a straight signal waveguide 201 and straight optical path 205, and SOA 200 comprises a crooked-path rib element 220 laterally defining a laser cavity 224. The operation of SOA 200 is similar to the operation of SOA 102 of FIG. 1 except that the optical signal 104 follows a straight path for the entire length of the device, while the laser cavity 224 follows the crooked

10   path. Generally speaking, when the lasing cavity must be separated from the signal path near the ends of the device to enable easier optical coupling to the outside world, it is preferable that the lasing cavity follow a crooked trajectory and that the signal waveguide follow a straight trajectory (as in FIG. 2) rather than vice versa (as in FIG. 1). This avoids losses in the optical signal 104 due to optical path bending. Furthermore, optical

15   path bending losses in the crooked laser cavity are more easily dealt with, $e.g.$, by increasing the laser excitation current. The amount of evanescent coupling experienced in the evanescent coupling region formed along the length L_{AMP} is similar to that of the SOA 100 of FIG. 1.

FIG. 3 illustrates a top view of the SOA 200 of FIG. 2 that includes further detail

20   regarding the electrical contacts for the laser cavity 224. In particular, along the top of the ridge element 210 is an intermediate ohmic contact 304 comprising a low band gap material such as heavily p-doped InGaAsP. A metallic contact 306 is formed above the path of the laser cavity, being formed on top of the intermediate ohmic contact 304 when coinciding with the ridge element 210. Also shown in FIG. 3 is laser output light 302

25   which, depending on the reflectivities of the material placed at the ends of the laser cavity 224, can be emitted from one or from both ends of the laser cavity 224. The laser output light 302 generally remains unused. Importantly, the laser output light 302 should be kept away from the output path of the optical signal 104.

As indicated in FIG. 3, the metallic contact 306 needs to "climb" up the sides of

30   the ridge element 210 during certain intervals. Generally speaking, this presents no special problems in the fabrication of the SOA 200, especially if the ridge element 210 is

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formed by a wet etching process that results in sloped, rather than purely vertical, side walls.

FIGS. 4 and 5 illustrate the SOA 200 along a first cross-sectional view A-A' and a second cross-sectional view B-B', respectively. Shown in these views is a lower ohmic contact 402 and proton implanted regions 406 lying adjacent to the laser cavity 224. Importantly, subsequent to the growth of the material layer from which ridge element 210 will be formed, the wafer must be proton implanted in all regions except along the laser cavity 224, thereby forming proton implanted regions 406. The depth of the proton implantation regions 406 can vary somewhat but generally must be deep enough to penetrate the active gain medium layer 214. As known in the art, the proton-implanted regions 406 are electrically nonconductive, and therefore current will be confined to the laser cavity 224 as desired. Also shown in FIGS. 4-5 are dotted-line regions that approximate electromagnetic field boundaries of the optical signal path 205 and a lasing field path 403. As indicated in FIG. 5, these fields will at least slightly overlap when the signal waveguide 201 lies near the laser cavity 224, consistent with the evanescent coupling that exists between the signal waveguide 201 and laser cavity 224, and energy from the lasing field will be coupled into the signal waveguide 201 to amplify the optical signal 104.

FIG. 6 illustrates a top view of an SOA 600 in accordance with a preferred embodiment. SOA 600 is similar to the SOA 200 of FIG. 2, comprising a signal waveguide 601 laterally defined by a ridge element 610 and a laser cavity 624 positioned near the signal waveguide 601, except that the laser cavity 624 of SOA 600 is segmented into three different sections between its end mirrors. The three sections are electrically isolated from each other and supplied with different currents from separate electrical contacts. In particular, a main electrical contact 606 supplies electrical current to the central part of the laser cavity 624 that passes near the optical signal path, while end electrical contacts 607 and 609 supply electrical current to end portions of the laser cavity 624.

The SOA 600 is proton-implanted in connecting strips 613 and 615, also termed intra-laser cavity segmentation strips, lying between the respective laser segments to provide electrical isolation among the sections. Preferably, because optical losses in a

non-excited, non-disordered gain medium can be quite large, the gain medium of the laser cavity 624 is disordered along the connecting strips 613 and 615 to minimize optical losses at these locations. Alternatively, the gain medium is left intact along the connecting strips 613 and 615, and the electrical resistivity profiles therein are tailored in

5   a manner similar to that described in U.S. Ser. No. 09/972,146, filed October 4, 2001, *supra*, such that a modest amount of excitation current sufficient to pump the gain medium to transparency bleeds over from the adjacent laser cavity segments.

Explicitly indicated in FIG. 6 is an evanescent coupling region 631 that is formed at areas where the signal waveguide 601 vertically coincides with the laser cavity 224.

10   Areas along the signal waveguide 610 that are not in the evanescent coupling region 631 are identified as regions 633. Preferably, the gain medium layer of the SOA 600 is also disordered underneath the signal waveguide 601 at regions 633 lying outside the evanescent coupling region 631, for reducing signal loss in those areas. Alternatively, the regions 633 can be bypassed altogether by trenching a V-shaped groove inward along the

15   end regions 633 and etching new signal waveguide end facets very close to the evanescent coupling region 633. The V-shaped groove accommodates placement of the new end facets and also provides physical support for the optical fibers. The lasing path of the laser cavity 624 follows a crooked or S-like trajectory between its end mirrors.

As indicated by the single laser cavity output 625 in FIG. 6 having an output

20   power of P_{LC}, it is presumed herein that one end of the laser cavity 624 has a fully reflective mirror and therefore all optical laser power P_{LC} is emitted out the other end. According to a preferred embodiment, the different segments of the laser cavity 624 are pumped with different excitation currents to achieve one or more desired effects in the operation of SOA 600. According to a preferred embodiment, when the laser cavity 624

25   is lasing, electrical current through the end segments 607 and 609 may be varied to adjust the amount of signal gain achieved in the main portion 606, thus achieving the result of gain adjustability while also achieving the result of clamped gain operation.

FIG. 7 illustrates a conceptual plot of emitted laser power P_{LC} versus excitation currents in the SOA of FIG. 6. FIG. 8A illustrates a conceptual plot of SOA gain

30   P_{OUT}/P_{IN} versus output signal power P_{OUT} for the optical signal 104. For simplicity and clarity of disclosure, it will be presumed that the electrical currents supplied to the end

portions 607 and 609 are identical and represented by the single variable I_{end}, it being understood that the scope of the preferred embodiments is not so limited. Indeed, it is to be appreciated that effects similar to those described herein can be realized with only one end segment instead of two end segments as in the example of FIG. 6, or alternatively can

5   be realized with more than two end segments without departing from the scope of the preferred embodiments. A first curve 702 shows output laser power P_{LC} versus excitation current I_{MAIN} in the main laser cavity 606 when $I_{end} = 0$. In this situation, the ends of the laser cavity 624 are "dark" and lasing is inhibited for all practical values of I_{MAIN}. At both exemplary operating points O0 and O3 of FIG. 7, there is no lasing action in the

10 laser cavity 624, and only spontaneous emission occurs. In FIG. 8A, the gain curve g0 corresponds to the operating point O0 in FIG. 7, the gain curve g3 corresponds to the operating point O3 in FIG. 7, and so on. As indicated by the gain curves g0 and g3, there is no gain clamping in this region of operation, and for all but the lowest signal powers the SOA will experience signal dependent gain, crosstalk, and other adverse effects due

15 to gain saturation effects.

However, when end segment current I_{end} is increased to an intermediate level I1, the ends of the laser cavity 624 begin to facilitate lasing action such that, if the main segment current I_{MAIN} is increased past a first threshold level I_{TH1}, lasing action occurs. Shown in FIG. 7 is a curve 704 corresponding $I_{end} = I1$, including operating points O1

20 and O4. Provided that the laser cavity 624 is lasing, the optical signal gains g1 and g4 corresponding to O1 and O4, respectively, are clamped to the same value. However, although the SOA gains are the same for operating points O1 and O4, the SOA optical saturation power (*i.e.*, the output power level at which the gain curves g1 and g4 drop off by -3dB or more in FIG. 8A) is higher for the operating point O4 than for the operating

25 point O1. This is consistent with the fact that the excitation current I_{MAIN} is greater for operating point O4 than for operating point O1, and hence the photon density is higher.

When the end segment current I_{end} is increased to an even greater level I2, the ends of the laser cavity 624 facilitate lasing action even more. This, in turn, reduces the amount of main segment current I_{MAIN} needed to cause lasing action. Curve 706

30 corresponds to the greater end segment current $I_{end} = I2$, including operating points O2 and O5. Again, provided that the laser cavity 624 is lasing, the optical signal gains g2

and g5 corresponding to O2 and O5, respectively, are clamped to the same value. Again, the SOA saturation power for operating point O5 is higher than the SOA saturation power for operating point O2, consistent with the fact that its corresponding main segment current level I_{MAIN} is greater. In accordance with a preferred embodiment, and as will be

5   described further *infra*, the end segment current I_{end} may be advantageously adjusted to achieve different power, gain, and/or noise-reducing objectives, which becomes particularly useful when multiple lasing cavities are used to provide amplification energy for the optical signal 104.

FIG. 8B illustrates a conceptual plot of emitted laser power P_{LC} versus excitation

10   current I_{MAIN}, and FIG. 8C illustrates a conceptual plot of SOA gain P_{OUT}/P_{IN} versus output signal power P_{OUT} for the optical signal 104, for the SOA of FIG. 6 at different operating points O6, O7, and O8. In this example, the main segment current I_{MAIN} is kept constant at a value I_{MAIN0}, while the end current I_{end} is varied. As illustrated in FIG. 8C, if the main segment current I_{MAIN} is kept constant above the lasing threshold, the SOA

15   gain and saturation power both increase with increasing amounts of end current I_{end}.

FIG. 9 illustrates a conceptual curve 900 of optical medium gain per unit distance versus wavelength corresponding to the active medium of the SOA 200 or 600 for a fixed excitation current. By way of example, for an SOA based on known InGaAsP/InGaAs/InP gain media, the total width of the curve 900 may extend from about

20   1500 nm to 1580 nm. As used herein, the term "wavelength region of operation" denotes the specified set of wavelengths for which an SOA will properly amplify an optical signal according to desired parameters. For any SOA, of course, the wavelength region of operation must lie somewhere inside the curve 900 of FIG. 9. More particularly, the wavelength region of operation is selected along a portion of the curve 900 where there is

25   high and reasonably constant gain for proper operation, *e.g.*, the region 902 of FIG. 9 extending from a lower operating wavelength λ_{min} to an upper operating wavelength λ_{max}. By way of example, the wavelength region of operation 902 may extend from $\lambda_{min} = 1520$ nm to $\lambda_{max} = 1560$ nm.

Importantly, for usability reasons, it is desirable to provide an SOA with a

30   continuous wavelength region of operation 902 that, in addition to having a low ASE level, is substantially free of extraneous optical signals in that wavelength region.

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Preferably, if extraneous signals do exist in the output due to the way the SOA operates, these extraneous signals should be at wavelengths lying outside the operating range $[\lambda_{min}, \lambda_{max}]$ so they can be filtered out. As used herein, the term "excitation wavelength(s)" refers to the wavelength(s) at which the laser cavity of the SOA 200 or

5   600 is lasing. According to a preferred embodiment, to ensure that the amplified output is substantially free of extraneous optical signals in the wavelength region of operation, the nominal excitation wavelength of the laser cavity that is positioned near the optical signal path is kept outside the wavelength region of operation 902, but sufficiently inside the curve 900 to provide sufficient excitation of the gain medium. In this way, if light

10   from the laser cavity leaks into the output by one or more undesired effects (some of which are avoidable and some not), these extraneous signals can be filtered out.

According to a preferred embodiment, an SOA such as the SOA 200 of FIG. 2 is provided having a wavelength region of operation such as region 902 of FIG. 9, while having a nominal excitation wavelength that lies within region 906 separated from the

15   wavelength region of operation 902 by a buffer region 904. The buffer region 904 has a predetermined width selected such that any extraneous power that might incidentally couple from the laser cavity into the output signal can be easily filtered out using inexpensive thin film filters or other filter types. In one preferred embodiment, the buffer region 904 has a width in the range of 0.1 nm to 5 nm, with the higher widths requiring

20   less expensive filtering equipment.

Although described above in terms of an SOA having a laser cavity separated from the signal waveguide and evanescently coupled thereto, the selection of an excitation wavelength outside the wavelength region of operation is also advantageously applied to preferred embodiments in which the gain medium of the laser cavity is

25   coextensive with the gain medium of the signal waveguide, as described in Ser. No. 09/972,146, *supra*. By coextensive, it is meant that the laser cavity gain medium is integral with the signal waveguide gain medium at locations of vertical coincidence between the laser cavity and the signal waveguide, *i.e.*, the same active material forms both the laser cavity gain medium and the signal waveguide gain medium there. Stated

30   another way, by coextensive it is meant that the laser cavity gain medium is also laterally coincident with the signal waveguide gain medium at locations of vertical coincidence

between the laser cavity and the signal waveguide. An amplification region is formed at the locations of vertical coincidence, the optical signal being amplified by virtue of a population inversion in the gain medium established by the laser cavity. The optical signal is amplified the signal amplification region using energy provided by the laser

5 cavity.

In contrast, in the SOA of FIG. 6 and generally in the evanescent coupling cases described herein, the gain medium of the laser cavity is not coextensive with the guiding layer of the signal waveguide at locations of vertical coincidence between the laser cavity and the signal waveguide. In FIG. 6, for example, the region 631 represents the locations

10 of vertical coincidence between the laser cavity 624 and the signal waveguide 601. The gain medium of the laser cavity is not coextensive with the guiding layer of the signal waveguide in the region 631 because there is vertical separation between them there. An amplification region is nevertheless formed in the region 631, with the optical signal still being amplified by virtue of a population inversion in the gain medium established by the

15 laser cavity. However, it is by an evanescent coupling effect that the optical signal is amplified the signal amplification region using energy provided by the laser cavity.

Depending on the specific dimensions of the SOA 200 of FIG. 2, a substantial amount of undesired extraneous signal energy lying between λ_{min} and λ_{max} could potentially find its way into the output signal regardless of the nominal excitation

20 wavelength. This is an undesired phenomenon because such signals cannot be filtered out by low-cost filters and in some cases cannot be filtered out at all. A first cause of such extraneous signal leakage is conventional scattering (*e.g.*, due to imperfections, reflections, etc.) of longitudinal modes of the laser light that intrude into the region 902 between λ_{min} and λ_{max}. This is especially troublesome for longer lasing cavity lengths,

25 because the number of permitted longitudinal modes falling inside the wavelength region of operation 902 can be relatively high. By way of example, for a 3 mm cavity length the longitudinal modes are spaced apart by about 0.1 nm, while for a 30 µm cavity length the spacing is about 10 nm.

A second cause of such extraneous signal energy can arise from optical injection

30 locking effects. As known in the art, light from a master laser that is injected into a slave laser can cause the slave laser to "lock" onto the wavelengths of the master laser. Even

worse, if multiple wavelengths are injected that are close enough to the nominal slave laser wavelength, the slave laser can erratically jump among the different injected wavelengths, sometimes even in a chaotic fashion. Moreover, when there are multiple laser cavities energizing the SOA (as will be described *infra*), these multiple cavities can

5   start locking onto each other and, in combination with scattering effects, can cause extraneous energy between λ_{min} and λ_{max} to appear in the output. Injection locking effects can become particularly troublesome near the output of the SOA device where the power of the amplified optical signal might approach the order of magnitude of the power of the laser cavity. Further information on optical injection locking can be found in Bordonalli,

10   "High-Performance Phase Locking of Wide Linewidth Semiconductor Lasers by Combined Use of Optical Injection Locking and Optical Phase-Lock Loop," J. Lightwave Tech. Vol. 17, No. 2, pp. 328-342 (February 1999), which is incorporated by reference herein.

FIG. 10 illustrates a top view of an SOA 1000 in accordance with a preferred

15   embodiment that minimizes extraneous output energy caused by scattering and/or optical injection locking effects by ensuring monochromatic behavior in the excitation laser cavity. The SOA 1000 is similar to the SOA 200 of FIG. 2, comprising a ridge element 1010 for guiding the optical signal 104 along a signal waveguide 1001 as well as a subsurface laser cavity 1024, except that distributed Bragg reflectors (DBRs) 1028 are

20   provided near the end facets of the laser cavity 1024. As known in the art, DBRs 1028 can be readily inscribed that cause monochromatic operation to be achieved in the laser cavity 1024. Preferably, as shown in FIG. 10, the DBRs 1028 are formed at the ends of the laser cavity 1024 at locations that do not evanescently couple to the optical signal. This avoids unwanted filtering of the optical signal itself, as well as other excess losses.

25   In an alternative preferred embodiment, distributed feedback laser (DFB) gratings may occupy the entire laser cavity 1024, although some undesired filtering of the optical signal itself might occur if implemented in the embodiment of FIG. 10. The DBR features 1028 may be used in combination with multiple electrical contact features, multi-segment laser cavity features, and other features described herein.

30   FIG. 11 illustrates a view of the SOA 1000 of FIG. 10 along a cross-section A-A', the SOA 1000 comprising material layers 1108, 1112-1118, and 1122 similar to the

material layers 208, 212-218, and 222 of FIG. 2, respectively, except that DBR grating features 1028 are inscribed into the second cladding layer 1118 prior to depositing the laser waveguiding material layer 1116. As known in the art, the inscribed gratings are generally separated by distance that is on the order of magnitude of a fraction of the

5 lasing wavelength. When properly designed, the laser output beam 1025 will be monochromatic and will lie in one of the desired lasing ranges 906 of FIG. 9. Any of a variety of methods may be used to form DBRs and/or DFB gratings. Generally speaking, in the preferred embodiment in which DBRs are inscribed, some extraneous wavelengths might appear if the laser cavity 1024 is pumped too hard with current. In the preferred

10 embodiment in which DFB gratings are inscribed, hard pumping of the laser cavity 1024 will be less problematic and monochromatic behavior maintained, particularly if a quarter-wave phase shifting mechanism is built into the DFB gratings as is known in the art. Although described above in terms of an SOA having a laser cavity separated from the signal waveguide and evanescently coupled thereto, the incorporation of DBRs or

15 DFB gratings into the excitation laser cavity is also advantageously applied to preferred embodiments in which the laser cavity is coextensive with the signal waveguide, as described in Ser. No. 09/972,146, *supra*.

FIG. 12 illustrates a top view of an SOA 1200 in accordance with a preferred embodiment that is similar to the SOA 200 of FIG. 2 except that its laser cavity 1224 is

20 collinear with the ridge element 1210 defining the signal waveguide 1201. Optionally, the SOA 1200 may be provided with DBRs or DFB gratings as described *supra* for minimizing extraneous output energy caused by scattering an/or optical injection locking effects. The SOA 1200 provides reduced signal losses as compared to the SOA 200 of FIG. 2 because there is amplification along the entire optical signal path. However, the

25 SOA 1200 has a drawback in that there is minimal separation of the optical signal path and laser cavity outputs at the edges of the device, thereby necessitating bulk optical elements to couple light into and out of the device.

FIGS. 13 and 14 illustrate an SOA 1300 in accordance with a preferred embodiment that provides variable signal gain along the optical path by gradually

30 increasing the evanescent coupling distance between the signal waveguide 1301 and laser cavity 1324. The SOA 1300 comprises material layers 1414-1418 and 1422 similar to

the material layers 1214-1218 and 1222 of FIG. 12, respectively. However, directly above the gain medium layer 1414, a spacer layer 1411 of increasing vertical thickness is deposited during the fabrication process using any of a variety of known methods, the spacer layer 1411 having a thickness of zero at one end and a thickness of "d" at the other

5   end. The first cladding layer 1412, guiding layer 1408, and ridge element 1310 are then formed in a normal fashion above the spacer layer 1411. The spacer layer 1411 should have an index of refraction identical to that of the first cladding layer 1412 for proper vertical confinement of the lasing field. Varying the evanescent coupling distance to adjust signal gain may be especially advantageous when achieved in conjunction with the

10 use of multiple laser cavity segments, multiple laser cavities, and/or multiple differing laser cavity electrical excitations, whereby any of a variety of different power, gain, and/or noise-reducing objectives can be realized.

FIG. 15 illustrates an SOA 1500 in accordance with a preferred embodiment that is similar to the SOA 1300 of FIGS. 13-14, comprising a ridge element 1510 for guiding

15 the optical signal along a signal waveguide 1501 as well as a collinear subsurface laser cavity 1524, but in which the laser cavity 1524 is divided into multiple segments 1507, 1506, and 1509 having different electrical contacts for permitting different electrical excitation currents. In a manner similar to the SOA 600 of FIG. 6, connecting strips 1513 and 1515 lying between successive laser segments are proton implanted for providing

20 electrical isolation, and the active gain medium is also disordered at these locations. Alternatively, the gain medium is left ordered along the connecting strips, and the electrical resistivity profiles of the connecting strips are tailored such that a modest amount of excitation current sufficient to pump the gain medium to transparency is supplied. The SOA 1500 may optionally have DBRs or DFB gratings for purposes

25 described *supra*. More generally, any of a variety of combinations of the following features according to the preferred embodiments may be used for realizing different power, gain, noise reduction, extraneous signal reduction, or other objectives: multiple laser cavity segments, multiple laser cavity electrical contacts, variable evanescent coupling gain, integration of DBRs and/or DFB gratings, and other features described

30 herein.

FIG. 16 illustrates an SOA 1600 in accordance with a preferred embodiment, comprising multiple meandering transverse lasers 1624 that pass underneath a signal waveguide 1601 near their center portions. The lasing paths of the transverse lasers 1624 follow crooked or S-like trajectories between their end mirrors. SOA 1600 comprises

5   material layers similar to those of SOA 200 of FIG. 2, although the materials used may be altered to accommodate sharper bends in the lasing paths of the transverse lasers 1624 using methods described, for example, in the Loncar and Joannopoulos references, *supra*. Because laser light 1625 is emitted in the transverse direction well away from the path of the optical signal, the power of the transverse lasers 1624 can be raised to higher levels to

10   compensate for bending losses in the lasing paths. The overall width dimension of the SOA 1600 between the end facets (not shown) of the lasers 1624 will typically be not less than about 30 μm to permit sufficient lasing action. It is generally desirable to keep this dimension as short as possible to reduce overall electrical current requirements. Shown in FIG. 16 at the ends of each laser 1624 are DBRs 1628 that ensure monochromatic

15   lasing activity as described *supra*. In accordance with a preferred embodiment, the dimensions, evanescent coupling depths, and/or electrical excitation schemes of the several transverse lasers 1624 may differ from each other for realizing different power, gain, noise reduction, extraneous signal reduction, and other objectives.

FIG. 17 illustrates an SOA 1700 in accordance with a preferred embodiment,

20   comprising multiple meandering transverse lasers 1724a-1724e that pass underneath the signal waveguide 1701 near their center portions. The SOA 1700 is similar to the SOA 1600 except that each meandering transverse laser cavity is segmented into three segments, with each of the three segments being separately electrically excited by electrical contacts 1707, 1706, and 1709. The connecting strips lying between successive

25   laser segments are proton implanted for providing electrical isolation, and the active gain medium is also disordered at these locations. Alternatively, the gain medium is left ordered along the connecting strips, and the electrical resistivity profiles of the connecting strips are tailored such that a modest amount of excitation current sufficient to pump the gain medium to transparency is supplied.

30   According to a preferred embodiment, the meandering transverse laser cavities 1724a-1724e are identical to each other, but their excitation currents differ so as to

provide improved ASE noise performance. Exemplary schemes for adjusting the excitation currents for provide improved ASE noise performance are described *infra* with respect to FIGS. 22-24C.

According to an alternative preferred embodiment, equivalent ASE reduction

5   and/or other useful results are obtained by varying the end mirror reflectivities while keeping the excitation currents the same. In particular, where an end segment excitation current (*e.g.*, the current through segments 1707/1709 of FIG. 17) would be decreased, an equivalent result could be obtained by decreasing the end mirror reflectivity. Where an end segment excitation current would be increased, an equivalent result could be obtained

10   by increasing the end mirror reflectivity.

According to another preferred embodiment, equivalent ASE reduction and/or other useful results are obtained by varying the material characteristics of the gain medium itself across the successive laser cavities. By way of example and not by way of limitation, where bulk active $In_xGa_{1-x}As_yP_{1-y}$ is used in the gain medium, the variables x

15   and y can be varied during fabrication. As a further example, differing oxide preferential growth processes and/or other fabrication variations may be applied in forming the gain medium portions of successive laser cavities. In still another preferred embodiment, the thickness of the gain medium is altered among successive laser cavities. In still another preferred embodiment, cavity width and/or depth are altered among successive laser

20   cavities. Various combinations of the above items, which include excitation current magnitudes, end mirror reflectivities, gain medium materials, gain medium thicknesses, and cavity dimensions can be varied to achieve ASE reduction and/or other useful results according to the preferred embodiments. Generally speaking, however, the only parameters dynamically changeable during device operation are the successive excitation

25   currents (or the successive injected photon densities for optical injection pumping), with the remaining parameters being fixed after the device is fabricated.

FIG. 18 illustrates steps for fabricating an SOA in accordance with a preferred embodiment. The beginning substrate, comprising for example an InP substrate material, will generally be larger in both width and length than the finished SOA itself. At step

30   1802, beginning with a substrate such as an InP substrate, an n-InP cladding layer is formed on the substrate that, with respect to the exemplary embodiment of FIG. 2,

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corresponds to second cladding layer 218. At step 1804, a void corresponding to the rib element 220 is etched into the second cladding layer. In preferred embodiments in which multiple laser cavities are formed, there will be multiple such voids formed. At step 1806, DBRs and/or DFB gratings are inscribed. It is to be appreciated that the DBR/DFB

5 gratings may be formed in layers other than the second cladding layer 218, or may be formed in other ways such as by variation of the refractive index of the waveguide material or by lateral formation or bonding of DBR structures onto the ends of the laser cavities. At step 1808 the waveguiding layer 216, comprising for example waveguiding n-InGaAsP, is formed above the second cladding layer 218, which includes the filling in

10 of the rib element void(s). If different material is used for the waveguiding layer 216, it should have an index of refraction sufficiently different than the index of refraction of the second cladding layer 218 to effectuate the DBR/DFB gratings. At step 1810 the gain medium layer 214 is formed, comprising for example bulk active indium gallium arsenide phosphide, $e.g.$, $In_{0.7}Ga_{0.3}As_{0.7}P_{0.3}$, or multiple quantum wells (MQWs)

15 according to a InGaAsP/InGaAs/InP material system. Also at step 1810 the first cladding layer 212 is formed, comprising for example p-InP, and signal guiding layer 208 is formed, comprising for example waveguiding p-InGaAsP. Also at step 1810, a laterally uniform layer of p-InP is formed that will eventually become the ridge element 210, and a thin, laterally uniform layer of heavily doped p-InGaAsP is formed that will eventually

20 become the intermediate ohmic contact layer 304.

At step 1812, a mask is applied at all locations except those corresponding to intra-laser cavity segmentation strips ($e.g.$, the strips 613 and 615 of FIG. 6), a disordering ion implantation is performed, $e.g.$, using argon or helium, and the mask is removed. At step 1814, the wafer is heated to 800-900 degrees Celsius momentarily to

25 achieve quantum well disordering in the segmentation strips.

At step 1816, a mask is deposited across all areas corresponding to electrically conductive laser portions. For the preferred embodiment of FIG. 2, this mask is simply formed along a continuous strip above the rib element 220. However, there will be several such strips when multiple laser cavities are formed. If the laser cavity or cavities

30 are to be segmented into plural, electrically separate segments, there will be a separate mask element for each such segment. At step 1818 the wafer is proton implanted down

to the desired depth, which is usually a predetermined distance below the gain medium layer 214, and at step 1820 the mask is removed. At step 1822, a mask is applied to an area corresponding to ridge element 210, the intermediate ohmic contact layer and ridge layers are etched away at all non-masked locations to form the intermediate ohmic

5 contact 304 and ridge element 210, and the mask is removed. Step 1822 preferably comprises a wet etch process, which will cause the side walls of the ridge element 210 to be gently sloped for facilitating subsequent metallization.

At step 1824, the end facets are formed. For end facets that are on the sides of the device as in FIG. 16, a dry etching process is usually required because the end facets are

10 so close together (e.g., 30 μm – 100 μm). Any of a variety of known III-V material dry etching methods may be used. Cleaving or dry etching may be used to form the longitudinal end facets near the input and output of the device. Antireflection coatings are applied at the longitudinal end facets near the signal waveguide, and partially reflective coatings are applied at the longitudinal end facets near the laser cavity if

15 required. Also at step 1824, the steps of metallization, formation of bonds pads, etc. are performed using known methods. A polyimide filling layer is formed on the substrate adjacent to the SOA device to provide support for metallic connections between external bond pads and the upper electrical contacts of the laser cavities. Steps for forming optional additional optical devices on the same substrate, such as those described in

20 FIGS. 25-28 *infra*, are carried out subsequent to or in parallel with the steps 1802-1824 as required.

The above steps for fabricating an SOA in accordance with a preferred embodiment were described for a p-over-n buried heterostructure laser in which the signal waveguide is placed above the gain medium layer on the "p" side. As discussed

25 *supra*, in light of the present disclosure one skilled in the art would be readily able to construct the complementary n-over-p preferred embodiment, in which the signal waveguide is placed on the "n" side of the gain medium.

FIG. 19A illustrates a perspective view of an SOA 1900 in accordance with a preferred embodiment, in which an optical signal traveling down a signal waveguide is

30 amplified by an evanescent coupling effect with a plurality of transverse laser cavities. SOA 1900 comprises material layers 1908, 1912-1918, and 1922 similar to the material

layers 208, 212-218, and 222 of FIG. 2, and is similar to the SOA 1600 of FIG 16, except that transverse laser cavities 1924 are lasing in a direction perpendicular to path of the optical signal 104 in the evanescent coupling region. The evanescent coupling regions correspond to lateral areas where the optical signal path 1905 passes near the transverse

5 lasing fields, *i.e.*, where the ridge element 1910 crosses over the transverse laser cavities 1924 becoming vertically coincident therewith.

The mechanism by which energy from the lasing fields is coupled into the optical signal 104 is substantially unaffected by the particular orientation of the lasing fields, and so the operating characteristics of the SOA 1900 is substantially similar to the operating

10 characteristics of the SOAs *supra*. However, the geometry of the SOA 1900 allows for a greater number of separately pumped transverse laser cavities 1924, and is particularly suitable for applications in which variations of laser cavity excitation currents are varied to achieve desired effects such as noise reduction. The number of transverse laser cavities 1924 may vary greatly without departing from the scope of the preferred

15 embodiments. For example, if the transverse laser cavities 1924 are each 20 μm wide and separated by 5 μm, and if the overall longitudinal length of the device is 0.2 mm (200 μm), there would be 8 transverse laser cavities. If the transverse laser cavities 1924 are each 10 μm wide and separated by 2 μm, and if the overall longitudinal length of the device is 2.4 mm (2400 μm), there would be 200 transverse laser cavities. It is not

20 necessary for the transverse laser cavities 1924 to be identical to each other. By way of example, the transverse lasers 1924 may have different dimensions from each other. By way of further example, the transverse lasers 1924 may have different orientations from each other. In general, the transverse laser cavities 1924 may have substantially different characteristics that yield certain operating advantages, some examples of which are

25 described in detail *infra*. As indicated in FIG. 19A, the transverse laser cavities 1924 are electrically pumped by excitation currents supplied by separate electrical contacts 1906, with electrical isolation among laser cavities being provided by proton-implanted isolation zones 1930.

Depending on separation distances between adjacent transverse laser cavities,

30 proton implantation depths, proton implantation concentrations, layer thicknesses, and other factors, adjacent transverse laser cavities 1924 may experience optical coupling

effects. When the transverse laser cavities 1924 are placed close enough together, one or more optical coupling effects among them may be advantageously used. By way of example, the operating wavelengths of adjacent lasing cavities can lock together when the laser cavities are sufficiently close together, which can ensure monochromatic

5   operation of the laser cavities at a single, unified wavelength. As an incidental benefit, the DBR/DFB gratings on some of the transverse laser cavities could potentially be omitted without disturbing monochromatic lasing operation.

Alternatively, in other circumstances it may be desirable to minimize the amount of optical coupling between adjacent transverse laser cavities 1924. According to an

10 alternative preferred embodiment, one or more characteristics of adjacent transverse laser cavities 1924 are varied in order to avoid optical coupling effects therebetween, as will be described further *infra* with respect to FIGS. 29-30.

FIG. 19B illustrates a different perspective view of the SOA 1900 of FIG. 19A that, although still not to scale, is a closer conceptual illustration of the completed device.

15 More particularly, FIG. 19B shows structural features related to the electrical contacts 1906 that were omitted for clarity in FIG. 19A. Rather than rising above the rest of the device like a mesa as implied by FIG. 19A, the ridge element 1910 is actually formed by etching groove regions 1950 on either side of the ridge element 1910. On the other side of the grooves 1950 are spacer regions 1952 comprising the same material as the ridge

20 element 1910. The groove regions 1950 are made wide enough to ensure that the optical signal is laterally confined underneath the ridge element 1910. This configuration ensures a more consistent pumping of the gain medium along the length of the transverse laser cavities 1924 by providing consistent spacing between the electrical contacts 1906 and the gain medium layer 1914, while also providing for lateral confinement of the

25 optical signal 104. In the embodiment of FIG. 19B, the electrical contacts 1906 extend from near the front facets 1954 to near the back facets 1956 of the transverse laser cavities 1924, experiencing a temporary downward dip at the groove regions 1950. The electrical contacts 1906 make contact with bond pads 1958, which extend beyond the back facets 1956 to make contact with external current sources. As they extend

30 backward past the back facets 1956, the bond pads 1958 are supported by a planarization material 1960 such as polyimide. An HR coating 1962 is applied to the back facets 1956

separating the transverse laser cavities 1924 from the planarization material 1960. Because the longitudinal length of the SOA 1900 between the input and output end facets is quite long, *e.g.*, 200 μm - 2000 μm or greater, the longitudinal end facets may be cleaved. In contrast, the front facets 1954 and back facets 1956 of the transverse laser

5 cavities are reactive ion etched laser diode facets. For clarity of representation, the rib feature details between the laser waveguiding layer 1916 and second cladding layer 1918 are omitted in FIG. 19B.

The overall width dimension of the SOA 1900 between the end facets 1954 and 1956 will typically be not less than about 30 μm to permit sufficient lasing action. It is

10 generally desirable to keep this dimension as short as possible to reduce overall electrical current requirements. The SOA 1900 may comprise laser cavities that are in accordance with one or more of the following references, each of which is incorporated by reference herein: Hofling et. al., "Short-Cavity Edge-Emitting Lasers With Deeply Etched Distributed Bragg Mirrors," Electronics Letters, Vol. 35, No. 2 (January 21, 1999); and

15 Charles, P., "On-Wafer Facet Processing for Low Cost Optoelectronic Components," Electronics Letters, Vol. 33, No. 16 (July 31, 1997).

FIG. 20 illustrates a simplified top view of an SOA 2000 in accordance with a preferred embodiment that is similar to the SOA 1900 of FIGS. 19A-19B except that the transverse laser cavities are segmented. SOA 2000 comprises a signal waveguide 2001

20 that guides an optical signal 104 from an input to an output. For simplicity and clarity of disclosure, the ridge element needed to provide horizontal confinement of the optical signal 104 is omitted from FIG. 20. SOA 2000 comprises a plurality of transverse laser cavities 2024, each comprising a main segment 2006 and two end segments 2007 and 2009, respectively. Each laser cavity segment is supplied with a separate electrical

25 pumping current. Thin ion-implanted connecting strips 2013 and 2015 divide the segments and provide electrical isolation between them, the gain medium in these strips being disordered to provide optical continuity among the segments. Alternatively, the gain medium is left ordered along the connecting strips 2013 and 2015, and the electrical resistivity profiles are tailored such that a modest amount of excitation current sufficient

30 to pump the gain medium to transparency is provided.

According to a preferred embodiment, a first set of the transverse laser cavities 2024 may have end segments 2007/2009 that are turned "on" such that, for their respective portions of the signal waveguide 2001, there will be lasing and therefore gain-clamped amplification when the main segment 2006 has a current above a specified

5   threshold current. However, a second set of transverse laser cavities 2024 may have end segments 2007/2009 that are turned "off" such that there is no lasing and no gain clamped amplification along their respective portions of the signal waveguide 2001. Along the non-clamped portions of the signal waveguide 2001, nonlinear effects associated with gain saturation can occur. The arrangement of "on" and "off" cavities

10 may be fixed during operation, or alternatively may be dynamically altered or modulated with external signals to achieve a desired signal processing operation. The SOA 2000 represents a dynamically adjustable, multi-purpose optical signal processing device that allows gain-clamped amplification along a first set of longitudinal segments and non-clamped amplification along a second set of longitudinal segments. Applications for

15 such a multi-purpose device may be found in the fields of optical gating, wavelength conversion, optical signal regeneration, signal equalization, and other fields. For example, one suitable signal equalizer in accordance with a preferred embodiment comprises a first longitudinal section having gain-clamped amplification, followed by a second longitudinal section having a non-gain clamped amplification, followed by a third

20 longitudinal section having a gain-clamped amplification, the signal equalizer operating according to a boost-clip-boost equalization method.

While the transverse laser cavities of FIGS. 19A-19B and FIG. 20 are shown as being identical for simplicity and clarity of description, it is to be appreciated that they may vary greatly in size, shape, orientation, number of electrical contacts, material types,

25 and other features without departing from the scope of the preferred embodiments.

FIG. 21 illustrates a top view of an SOA 2100 in accordance with a preferred embodiment similar to the SOA 1900 of FIGS. 19A-19B except that the transverse laser cavities are tapered to reduce required pumping currents. SOA 2100 comprises a ridge element 2110 laterally defining a signal waveguide 2001, and a plurality of transverse

30 laser cavities 2124. As indicated in FIG. 21, each of the transverse laser cavities 2124 comprises a central region 2140 that passes nearby the optical signal 104 and that

evanescently provides signal amplification. The width of the central region 2140 should be a maximum because that width directly affects the amount of signal amplification. Each of the transverse laser cavities 2124 further comprises a transition region 2142 that tapers the width of the laser cavity down to a minimum width at an end region 2144. The tapers are effectuated by adjusting the shape of the ion implantation mask (see FIG. 18, steps 1812-1814) and the shape of the metallic electrical contacts during device fabrication. Electrical current requirements are reduced as compared to non-tapered laser cavities, because there is less volume of active gain medium that requires pumping.

FIGS. 22-24C illustrate alternative schemes for varying the pumping currents among several multi-segment transverse lasers of an SOA according to a preferred embodiment, whereby ASE noise in the output is reduced. FIG. 22 illustrates a top view of an exemplary SOA used in describing the alternative schemes. FIGS. 23-24A illustrate operating parameters according to a first ASE reduction scheme, while FIGS. 24B-24C illustrate operating parameters according to a second ASE reduction scheme. The first ASE reduction scheme is operable when, for a given transverse laser cavity "x", there is a sublinear relationship between (i) spontaneous emission noise N_x added to the optical signal, and (ii) signal gain g_x. By sublinear, it is meant that for a given percentage change in signal gain ($\Delta g_x/g_x$), there is a lesser percentage change in the spontaneous emission noise ($\Delta N_x/N_x$). The second ASE reduction scheme is operable when there is a superlinear relationship between N_x and g_x, $i.e.$, where a given percentage change in signal gain results in a greater percentage change in the spontaneous emission noise.

It is to be appreciated that, for simplicity and clarity of description, the SOA used in this example has only four transverse laser cavities. In practical devices there may be a substantially greater number of transverse laser cavities, or as few as two transverse laser cavities.

FIG. 22 illustrates a top view of an SOA 2200 similar to the SOA 2000 of FIG. 20 except having only four transverse laser cavities 2201, 2202, 2203, and 2204 that evanescently couple into a signal waveguide 2250 to amplify the optical signal 104. Each laser cavity comprises a main segment 2206 and end segments 2207 and 2209, respectively, each of the segments being separately pumped.

The notational scheme for FIGS. 22-24C is now described. Any given laser cavity in FIG. 22 is numbered 220x, where x = 1, 2, 3, or 4. It will be presumed that the electrical currents supplied to the end portions 2207 and 2209 of any given laser cavity 200x are identical and represented by the single variable I_{endx}, it being understood that the

5 scope of the preferred embodiments is not so limited. The main segment of each laser cavity 200x is supplied with an electrical current I_{MAINx}. Each laser cavity 220x produces laser light having a power of P_{LCx}. For each laser cavity 200x, an incoming optical power P_{x-1} encounters a corresponding portion of the signal waveguide 2250 and is amplified to produce an outgoing power P_x, resulting in a signal gain of $g_x = P_x/P_{x-1}$. The incoming

10 power P_0 corresponding to the first laser cavity 2201 represents the optical signal 104 at the overall device input, while the outgoing power P_4 corresponding to the last laser cavity 2204 represents the optical signal 104 at the overall device output.

According to a first preferred embodiment of an ASE reduction scheme operable when there is a sublinear relationship between spontaneous emission noise and signal gain, the

15 end segments are provided with progressively increasing electrical currents, $i.e.$, $I_{end1} <$ $I_{end2} < I_{end3} < I_{end4}$, and each main segment is provided with an electrical current I_{MAINx} sufficient to induce lasing action in a manner indicated in FIG. 23. FIG. 23 illustrates a conceptual plot of the laser cavity output power P_{LCx} (which is itself unused) versus excitation current I_{MAINx} according to the first ASE reduction scheme. The preferred

20 operating points for the respective laser cavities are denoted by O1, O2, O3, and O4 in FIG. 23. FIG. 24 illustrates plots of signal gains g1, g2, g3, and g4 versus output power for each of the operating points O1, O2, O3, and O4, respectively. The first laser cavity 2201 yields the greatest gain magnitude and the lowest output saturation power. The second laser cavity 2202 yields a lesser gain magnitude and a higher output saturation

25 power, and so on through laser cavity 2204, which yields the lowest gain magnitude but the highest output saturation power. The increases in output saturation power are concomitant with the need for such higher saturation powers, because the optical signal itself is getting large as it nears the SOA output. Where there is a sublinear relationship between spontaneous emission noise and signal gain, the scheme of FIGS. 23-24A will

30 improve ASE performance as compared to a scenario in which all of the excitation currents and all of the gains of the transverse laser cavities 220x are kept the same.

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According to a second preferred embodiment of an ASE reduction scheme operable when there is a superlinear relationship between spontaneous emission noise and signal gain, the end segments are provided with progressively decreasing electrical currents, i.e., $I_{end1} > I_{end2} > I_{end3} > I_{end4}$, and each main segment is provided with an

5 electrical current I_{MAINx} sufficient to induce lasing action in a manner indicated in FIG. 24B. FIG. 24B illustrates a conceptual plot of the laser cavity output power P_{LCx} (which is itself unused) versus excitation current I_{MAINx} according to the second ASE reduction scheme. The preferred operating points for the respective laser cavities are denoted by O1, O2, O3, and O4 in FIG. 24B. FIG. 24C illustrates plots of signal gains g1, g2, g3,

10 and g4 versus output power for each of the operating points O1, O2, O3, and O4. The first laser cavity 2201 yields the lowest gain magnitude and the lowest output saturation power. The second laser cavity 2202 yields a greater gain magnitude and a higher output saturation power, and so on through laser cavity 2204, which yields the highest gain magnitude and the highest output saturation power. The increases in output saturation

15 power are concomitant with the need for such higher saturation powers, because the optical signal itself is getting large as it nears the SOA output. Where there is a superlinear relationship between spontaneous emission noise and signal gain, the scheme of FIGS. 24B-24C will improve ASE performance as compared to a scenario in which all of the excitation currents and all of the gains of the transverse laser cavities 220x are kept

20 the same.

It is to be appreciated that while electrical pumping currents of identical laser cavities are used to reduce ASE noise in the example of FIGS. 22-24C, other variations among the laser cavities may be used that achieve equivalent effects. For example, the individual or combined variations among successive laser cavities described *supra* with

25 respect to FIG. 17, which include excitation current magnitudes, end mirror reflectivities, gain medium materials, gain medium thicknesses, cavity dimensions, and optical injection densities can be varied to achieve ASE reduction and/or other useful results according to the preferred embodiments. In each case, the gain and the saturation power are varied along successive longitudinal portions of the optical signal path to improve

30 SOA performance as compared to configurations in which the gain and the saturation power remain uniform along successive longitudinal portions. Whether used separately

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or in combination with electrical current variations, such methods for reducing output noise in an SOA having a plurality of laser cavities that provide energy for amplification of the optical signal are within the scope of the preferred embodiments. By way of further example, within the scope of the preferred embodiments is an SOA having the

5   combined attributes of the embodiment of FIG. 20 and FIG. 22 to provide varied gain, gain clamped, and gain-unclamped operation for signal processing. It is to be further appreciated that these structures and methods for reducing ASE noise or achieving other desired effects are also advantageously applied to preferred embodiments in which the gain medium of the laser cavities is coextensive with the gain medium of the signal

10   waveguide, as described in Ser. No. 09/972,146, *supra*.

FIG. 25 illustrates a perspective view of an integrated optical amplifier 2500 in accordance with a preferred embodiment, comprising an SOA 2502 having multiple transverse laser cavities, and comprising a tunable vertical coupler filter 2504 integrated therewith on a common substrate 2506. The SOA 2502 is similar to one described in Ser.

15   No. 09/972,146, *supra*, in which the gain medium of the laser cavities is coextensive with the gain medium of the signal waveguide. It is to be appreciated, however, that the SOAs described herein, in which the laser gain medium is evanescently coupled with the optical signal, may be used as well. While having a variety of uses, the integrated optical amplifier 2500 is particularly useful as a power amplifier or line amplifier in wavelength

20   division multiplexed (WDM) communications applications. The integrated optical amplifier 2500 receives an optical signal 104 which is amplified by the SOA 2502 and filtered by the tunable vertical coupler filter 2504, which results in an amplified version of the optical signal 104 as well as an unused ASE noise output 2519 spatially separated therefrom.

25   The tunable vertical coupler filter 2504 shares cladding layers 2522 and 2526 with the SOA 2502, and further comprises an input signal guiding layer 2524 which may be a disordered extension of the gain medium layer of the SOA 2502, or which may comprise a different wave guiding material. The tunable vertical coupler filter 2504 may be similar to any of those described in Liu et. al., "Optical Add/Drop Multiplexers Based on X-

30   Crossing Vertical Coupler Filters," IEEE Photonics Technology Letters, Vol. 12, No. 4 (April 2000), which is incorporated by reference herein. The tunable vertical coupler

filter 2504 comprises a coupling layer 2530, a guiding layer 2532, an upper cladding layer 2534, and a contact layer 2536, and is broadly tunable by current injection or the application of an appropriate bias voltage.

FIG. 26 illustrates a perspective view of an optical detector 2600 having an integrated amplifier in accordance with a preferred embodiment. Optical detector 2600 comprises an SOA 2602 similar to the SOA 2502 of FIG. 25 integrated onto a common substrate 2608 with a tunable vertical coupler filter 2604 tuned to a wavelength λ_1, which in turn comprises a photodetector 2606 integrated therewith. Photodetector 2606 comprises a lower p-doped cladding layer 2642, an i-absorbing layer 2644, an upper n-doped cladding layer 2646, and lower and upper ohmic contacts 2640 and 2648, respectively. In operation, an optical signal 104 comprising an N-channel WDM signal having channels at $\lambda_1\lambda_2\lambda_3...\lambda_N$ is input to the SOA 2602, where it is amplified. At the tunable vertical coupler filter 2604, the channel at λ_1 gets removed and fed to photodetector 2606, where it is absorbed by the i-absorbing layer 2644. An electrical voltage proportional to the optical signal intensity of the λ_1 channel is output between contacts 2650 and 2652. Meanwhile, the remaining channels at $\lambda_2\lambda_3...\lambda_N$ pass through in amplified form. It should be appreciated that FIG. 26 is not necessarily to scale.

FIG. 27 illustrates a perspective view of an optical return-to-zero (RZ) source 2700 having an integrated power amplifier in accordance with a preferred embodiment. RZ source 2700 comprises a first electro-absorption (EA) modulator 2702, a second EA modulator 2704, and an SOA 2706 having multiple transverse laser cavities, all three devices being integrated onto a common substrate 2710. The SOA 2706 is similar to a preferred embodiment of Ser. No. 09/972,146, *supra*, in which the gain medium of the laser cavities is coextensive with the gain medium of the signal waveguide. It is to be appreciated, however, that the SOAs described herein, in which the laser gain medium is evanescently coupled with the optical signal, may be used as well. In general, the layers of the phase modulators 2702 and 2704 are extensions of the layers of the SOA 2706, except that EA modulating material 2734 must be provided instead of the gain medium layers between the electrical contacts (2730/2732 and 2738/2740, respectively) of the EA modulators 2702 and 2704. An additional cladding layer 2716 is provided in each EA modulator, as shown in FIG. 27. The SOA 2706 comprises upper electrical contacts

2712 and a lower electrical contact 2714. Importantly, all layers of the intermediate regions 2736 and 2742 should be electrically nonconductive to provide electrical isolation among the elements, either by use of inherently nonconductive materials or otherwise by proton implantation or other electrical passivation method.

5   In operation, the RZ source 2700 receives (i) an optical carrier signal 104, (ii) a binary data signal at a modulation rate M at the electrical inputs 2738/2740 of the second EA modulator, and (iii) a sinusoidal signal at frequency M at the electrical inputs 2730/2732 of the first EA modulator. An RZ-modulated data signal is output from the second EA modulator 2704, and is then amplified prior to transmission by the SOA 2706 10   to produce an amplified, modulated optical carrier.

Mathematically, the operation of the RZ source 2700 is similar to that described in Ougazzaden, A. et. al., "40 Gb/s Tandem Electro-Absorption Modulator," Optical Fiber Communication Conference and Exhibit, pp. PD14-1 to PD14-3, Optical Society of America, Anaheim, California (March 17-22, 2001), which is incorporated by reference 15   herein, whereby the first EA modulator 2702 operates like the Ougazzaden "carver" and the second EA modulator 2704 operates like the Ougazzaden "encoder". From a practical viewpoint, however, the RZ source 2700 has an advantage over the structure described in Ougazzaden, which integrates a conventional SOA inbetween the EA modulators. This is presumably done because the conventional SOA experiences data- 20   dependent gain fluctuations, and so it could not be placed after the second ("encoder") EA modulator because the encoded data is an unpredictable bit stream. Because the output of the first ("carver") EA modulator is a regular pattern, the data-dependent gain of the conventional SOA used in Ougazzaden can be tolerated and/or compensated. Disadvantageously, however, amplification of the optical signal prior to the "encoder" 25   EA modulator can cause a bleaching effect in that EA modulator, and therefore device performance is degraded. In contrast, because the SOA 2700 of FIG. 27 is gain-clamped and does not experience data-dependent gain fluctuations, it can be placed after the second EA modulator 2704 and the bleaching effects of Ougazzaden are avoided.

FIG. 28 illustrates a perspective view of an optical return-to-zero (RZ) source 30   2800 having an integrated power amplifier and chirp induction/compensation in accordance with a preferred embodiment. RZ source 2800 is similar to the RZ source

2700, comprising a first EA modulator 2802, a second EA modulator 2804, and an SOA 2806 similar to elements 2702, 2704, and 2706 of FIG. 27, respectively, integrated onto a common substrate 2810. However, a phase modulating element 2805 is inserted between the second EA modulator 2804 and the SOA 2806, which induces a chirp in the

5   modulated signal responsive to a voltage signal provided at electrical contacts 2850/2852 thereof. Chirp compensation can be provided, and/or additional chirp can be provided, which can be useful in certain dispersion compensating scenarios.

FIG. 29 illustrates a simplified top view of an SOA 2900 in accordance with a preferred embodiment. SOA 2900 that is similar to the SOA 1900 of FIGS. 19A-19B

10   except that it has an added feature in which successive transverse laser cavities comprise DFB gratings with different grating periods to avoid optical coupling effects among them. SOA 2900 comprises a signal waveguide 2901 with lateral confinement provided by a ridge element 2910 and a plurality of transverse laser cavities 2924, the lasing fields providing amplification energy for an optical signal 104 propagating down the signal

15   waveguide 2901 between an input 2952 and an output 2954.

As discussed *supra* with respect to FIG. 9, injection locking effects can become problematic if the power of the optical signal 104 near the output 2954 approaches the order of magnitude of the power of the transverse laser cavity nearest the output. If there is strong optical coupling among adjacent transverse laser cavities, the adverse effects of

20   the injection locking can ripple backward from the last transverse laser to previous transverse laser. According to a preferred embodiment, the transverse laser cavities 2924 comprise DFB gratings 2956 of different periods such that lasing action occurs at different wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$ that are sufficiently spaced apart in wavelength such that optical coupling effects among the transverse laser cavities 2924 is avoided.

25   Accordingly, the SOA 2900 is robust against adverse injection locking effects. DBR gratings of differing periods may also be used to achieve differing lasing wavelengths. Each of the wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$ should lie within in the lasing range 906 of FIG. 9, *supra.*

One advantage from a practical viewpoint is that substantial tolerances exist

30   between the intended set of wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$ and the actual real-world wavelengths at which the transverse laser cavities 2924 actually operate. The important

criterion is that they simply operate at different wavelengths. The actual operating wavelengths do not need high precision as long as they fall within the lasing range 906 of FIG. 9.

It is to be appreciated that any of a variety of structure and/or composition

5 variations among the different transverse laser cavities 2924 may be employed to counter injection locking effects in accordance with the preferred embodiments. For example, different material compositions for the gain media can be used to achieve lasing action at different wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$. As another example, one or more of the transverse laser cavities 2924 may comprise a coupled-cavity laser pair. Strongly monochromatic

10 behavior at a predetermined single lasing wavelength λ_i is achieved for each coupled-cavity laser pair. For a given laser pair, the signal waveguide 2901 only passes near one of the two lasers. The two lasers are coupled together via a small gap that is achieved by etching or cleaving. When the gap is achieved by cleaving, the lasers are commonly called cleaved coupled cavity lasers. The lasing wavelength for the coupled-cavity laser

15 pair is the wavelength(s) at which their individual longitudinal modes overlap. According to a preferred embodiment, each of the laser cavities has a longitudinal mode at the desired lasing wavelength λ_i, the wavelength λ_i lying in the lasing range 906 of FIG. 9, and the lengths of the laser cavities are similar but not identical. The coupled-cavity pair thereby lases at the desired lasing wavelength λ_i in a strongly monochromatic

20 manner, because the next permitted longitudinal mode is separated from λ_i by an amount that is substantially greater than the longitudinal mode spacing of either of the individual laser cavities when viewed in isolation. By proper selection of individual cavity lengths and other characteristics, the lasing wavelengths of the successive coupled-cavity laser pairs are controlled such that operation is achieved at different wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$,

25 respectively, thereby avoiding injection locking effects. In other preferred embodiments, the lengths of the coupled-cavity laser pair may be substantially asymmetric. The SOA 2900 may comprise laser cavities that are in accordance with Wiedmann et. al., "Singlemode Operation Of Deeply Etched Coupled Cavity Laser With DBR Facet," Electronics Letters, Vol. 36, No. 14 (July 6, 2000), which is incorporated by reference

30 herein.

FIG. 30 illustrates a simplified top view of an SOA 3000 in accordance with a preferred embodiment that is similar to the SOA 2900 of FIG. 29 except that the lasing wavelengths alternate between only two wavelengths λ_1 and λ_2. A primary advantage of the SOA 3000 over the SOA 2900 of FIG. 29 relates to ease of fabrication, as the same

5 two grating patterns can repeat. Because optical coupling between two laser cavities decreases substantially with increased spacing, the amount of optical coupling among transverse lasers having the wavelength λ_1 is very small, and the amount of optical coupling among transverse lasers having the wavelength λ_2 is very small.

FIG. 31 illustrates a top view of an SOA 3100 in accordance with a preferred

10 embodiment and related explanatory gain medium characteristic curves. SOA 3100 comprises an overall structure similar to that of the SOA 1900 of FIGS. 19A-19B, but is further adapted to take advantage of thermal shifts in the gain medium characteristic in order to increase efficiency. SOA 3100 comprises a transverse laser cavity 3124 divided into two separately excited segments 3106 and 3107 by an isolation region 3113, the

15 isolation region 3113 being proton-implanted to provide electrical isolation, the gain medium of the isolation region 3113 being disordered to provide optical continuity in the transverse laser cavity 3124. Alternatively, the gain medium is left ordered in the isolation region 3113, and the electrical resistivity profile is tailored such that a modest amount of excitation current sufficient to pump the gain medium to transparency is

20 supplied. For simplicity and clarity of explanation, only a single transverse laser cavity is shown, it being understood that there can be multiple transverse laser cavities. A ridge element 3110, shown in dotted lines instead of solid lines so that the bounds of laser segment 3106 are clear, provides lateral confinement for the optical signal 104 as it propagates down a signal waveguide 3101. The signal waveguide 3101 is in a plane

25 separate from the gain medium layer. In an alternative preferred embodiment, the signal waveguide 3101 is coextensive with the gain medium layer, as described in Ser. No. 09/972,146, *supra*. The laser segment 3106 passing near the signal waveguide 3101 is pumped with a current I_{MAIN}, while the other laser segment 3107 is pumped with a current I_{end}.

30 According to a preferred embodiment, the pump current I_{end} is made greater (or lesser) than the pump current I_{MAIN} by an amount sufficient to raise (or lower) the

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junction temperature in the laser segment 3107 above (or below) the junction temperature in the laser segment 3106. As indicated by the gain medium characteristic curves 3150 and 3152, the different junction temperatures cause a shift in the gain curves. As known in the art, the amount of shift is roughly 1 nm per degree Celsius. The curves are shifted

5   such that the gain curve 3150 of the gain medium of the laser segment 3107 peaks closer to the lasing wavelength λ_{LASING} (i.e., closer to the lasing range 906 of FIG. 9), while the gain curve 3152 of the gain medium of the main laser segment 3106 peaks closer to the signal wavelength λ_{LASING}. Operational efficiency of the SOA 3100 is thereby increased.

In an alternative preferred embodiment, equivalent efficiency increases can be

10   realized by altering other aspects of the laser segments 3106 and 3107 to achieve relative shifts in their gain medium characteristic curves. In one example, the gain medium characteristic curves are adjusted differently for the two sections using oxide preferential growth.

FIG. 32 illustrates a top view of an SOA array 3200 in accordance with a

15   preferred embodiment. SOA 3200 comprises an overall structure similar to that of the SOA 1900 of FIGS. 19A-19B, except that a plurality of signal waveguides 3201a-3201d share the same set of transverse laser cavities 3224. This is achieved by forming multiple ridge elements 3210a-3210d as indicated in FIG. 32. A plurality of optical signals 104a-104d are amplified as they pass from an input facet 3252 to an output facet 3254. The

20   respective optical signals 104a-104d are amplified by about the same factor. The transverse laser cavities 3224 operate as "ballast" energy sources for gain-clamped amplification of the optical signals 104a-104d, and can be referred to as transverse "ballast" lasers. For the embodiment of FIG. 32 and other preferred embodiments, the spectrum of the gain medium is preferably broadened using multiple quantum wells of

25   slightly different compositions among the different transverse lasers to achieve wider overall operating ranges. The signal waveguides 3201a-3201d are in a plane separate from the plane of the gain medium layer. In an alternative preferred embodiment, the signal waveguides 3201a-3201d are coextensive with the gain medium layer, as described in Ser. No. 09/972,146, supra. The SOA 3200 integrates well with planar lightwave

30   circuits and is well suited for a variety of devices in which high-density SOA arrays

could be useful, *e.g.*, optical switches, optical signal processors, array waveguides, and other devices.

FIG. 33 illustrates a top view of an SOA array 3300 in accordance with a preferred embodiment in which the "ballast" lasers are successive pairs of coupled-cavity

5 lasers. In the example of FIG. 33 there are two coupled-cavity pairs 3306/3308 and 3310/3312, although in general there can be any number of them. A trench 3305, filled with air or other material that provides sufficient refractive index differences, forms one facet of each laser, the opposite facets being shown as elements 3304 in FIG. 33. Signal waveguides 3301a-3301b are laterally defined by ridge elements 3310a-3310b,

10 respectively, the ridge elements being shown in dotted lines instead of solid lines so that the bounds of lasers are clear. As known in the art, each member of a coupled-cavity laser pair operates as a distinct laser cavity with its own pump current, gain, carrier densities, resonance conditions, and so forth, although their operating wavelength is the same. Advantageously, in the SOA 3300 the optical signals 104a-104b can be amplified

15 by different amounts as a function of different pump currents applied to the coupled-cavity laser pairs. The signal waveguides 3301a-3301b are in a plane separate from the plane of the gain medium layer. In an alternative preferred embodiment, the signal waveguides 3301a-3301b are coextensive with the gain medium layer, as described in Ser. No. 09/972,146, *supra*.

20 FIG. 34 illustrates a top view of an SOA array 3400 in accordance with a preferred embodiment that also provides different amplifications for different optical signals. SOA 3400 comprises an overall structure similar to that of the SOA 3200 of FIG. 32, comprising a plurality of transverse laser cavities 3424 and multiple ridge elements 3410a-3410d forming multiple signal waveguides 3401a-3401d guiding a

25 plurality of optical signals 104a-104d that are amplified as they pass from an input facet 3452 to an output facet 3454. However, for a final transverse cavity 3456 there are separate electrical contacts 3458a-3458d for each respective signal waveguide 3401a-3401d, with proton-implanted isolation zones 3460a-3460e being formed therearound. The gain medium layer is left intact (*i.e.*, not disordered) in the isolation zones 3460a-

30 3460e so that lasing cannot build up under any circumstance. The areas under the respective electrical contacts 3458a-3458d are pumped below transparency with different

amounts of current so that each serves as its own variable attenuator. Accordingly, the optical signals 104a-104d can be amplified by different, tunable amounts as they pass through the SOA array 3400. The signal waveguides 3401a-3401d are in a plane separate from the plane of the gain medium layer. In an alternative preferred embodiment, the

5 signal waveguides 3401a-3401d are coextensive with the gain medium layer, as described in Ser. No. 09/972,146, *supra*.

Whereas many alterations and modifications of the present invention will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that the particular embodiments shown and

10 described by way of illustration are in no way intended to be considered limiting. For example, while the laser cavities described in the preferred embodiments *supra* are index-guided using a rib element for lateral confinement, in other preferred embodiments the lateral confinement may be provided by epitaxially regrown material adjacent to the active medium. In such case, the gain medium is grown across the entire lateral extent of

15 the device and then etched away at locations other than the laser cavity strip, and a non-active material having an index of refraction less than that of the gain medium is epitaxially regrown adjacent to the gain medium strip. In still other preferred embodiments, the laser cavities are gain-guided. As another example, while current confinement described in the preferred embodiments *supra* was achieved by proton

20 implantation, in other preferred embodiments current confinement may be achieved by p-n blocking, Fe doping, or other methods.

By way of further example, although the preferred embodiments are described *supra* in terms of electrical pumping of the laser gain medium, the scope of the preferred embodiments is not so limited. The gain medium may alternatively be optically pumped,

25 wherein a light flux is introduced into the gain medium to achieve a population inversion. There are also other known methods that may be used for pumping, including chemical pumping where the population is achieved chemically, and other methods. As yet another example, although the preferred embodiments are described *supra* in terms of a static positional relationship between the excitation laser(s) and the signal waveguide, in

30 other preferred embodiments there is a dynamic positional relationship such that the amount of evanescent coupling is dynamically tunable. In still other preferred

embodiments, the positional relationship between the excitation laser(s) and the signal waveguide remains the same, while other parameters are adjusted or other mechanisms are employed to make the amount of evanescent coupling between the excitation laser(s) and the signal waveguide dynamically tunable.

5   As still another example, while evanescent coupling in the preferred embodiments *supra* was described in terms of a signal waveguide that was vertically separated from a laser waveguide by one or more material layers in an integrated wafer structure, in other preferred embodiments the evanescent coupling may be achieved by horizontal separation of the signal waveguide from the laser waveguide within the same set of one

10   or more material layers. Indeed, a variety of different barrier types between the signal waveguide and laser waveguide may be used in accordance with the preferred embodiments. Because gain-clamped amplification greatly facilitates the use of multilevel or n-ary data encoding schemes (n > 2), within the scope of the preferred embodiments is a multilevel data communications system comprising at least one gain-

15   clamped SOA in which signal amplification energy is provided by a nearby lasing field such as a transverse lasing field. As stated previously, each of these enhancements may be implemented in conjunction with the preferred embodiments of Ser. No. 09/972,146, *supra*, in which the gain medium of the laser cavities is coextensive with the signal waveguide. Therefore, reference to the details of the preferred embodiments is not

20   intended to limit their scope.